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Studies on the correlation between tropospheric and ionospheric fluctuations

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Abstract: Fluctuations in barometric pressure and those in the critical frequencies and virtual heights of ionospheric E, E_s and F_2 regions have been studied by applying the correlation technique to these fluctuations. Metorological data for Delhi, Ahmedabad, Alipur and Kodaikanal and ionospheric data for Delhi, Ahmedabad, Haringhata and Kodaikanal are considered for the above purpose. Some degree of correlation has been detected between barometric pressure variation and variation of f_0E, f_0E_s, h′E and h′E_s.

1. Introduction

Although considerable work has been done to correlate E_s ionisation with thunderstorms (Wilson 1925, Appleton and Naismith 1933, Ratcliffe and White 1933, 1934, Berkner and Wells 1937, Bhar and Syam 1937, Healey 1938, Best *et al* 1938, Mitra *et al* 1939, Rastogi 1962), analysis on the correlation of fluctuations of tropospheric parameter– barometric pressure with fluctuations in ionospheric parameters—electron density and virtual height is insufficient (Martyn 1934, Martyn and Pulley 1936, Beynon and Brown 1951, Kundu 1953, Bauer 1957, 1958). As the ionospheric and tropospheric fluctuations have smooth regular variations (Wilkes 1949, Greenhow and Neufeld 1955, Siebert 1961, Butler and Small 1963, Haurwitz 1964, Green 1965, Lindzen 1967) with the time of the day and the season, having superposed random irregularities (Munro 1950, 1953, Mitra 1952, Roy and Verma 1953, Hines 1959, Whitehead 1967, Kent and Wright 1968, Reid 1968, Chimonas 1969, Smith 1970, Cole 1970, Picquenard 1974) and as there are expected some common causes controlling their fluctuations, an investigation into the existence of any correlation amongst these fluctuations may be undertaken. And for the studies on the correlation of these ionospheric and tropospheric fluctuations, the variations of tropospheric parameters-barometric pressure, humidity and atmospheric electricity and those of ionospheric parameters—critical frequency and virtual height may be examined. Meteorological and ionospheric data are obtainable in a continuous series over a long period of time for many meteorological and ionospheric observatories in India and abroad. The data of barometric pressure, critical frequency and virtual height have been studied and correlation analysis has been made for the data collected at Delhi, Ahmedabad, Kodaikanal. Meteorological data from Alipur and ionospheric data from Haringhata have also been studied. Studies have all been based on the principle of determination of the correlation coefficients (Cook *et al* 1955, Lange 1967) in the variation of these trophospheric and ionospheric parameters.

2. Correlation technique

The present study is based on time series of observations on meteorological (M) and ionospheric (I) parameters having random irregularities superposed on their systematic diurnal and seasonal components which have smooth time-paths.

Given a series of observations $f(t)$, $t = 1, 2, \ldots, n$ the auto-correlation coefficient for log τ is defined as

$$\rho(\tau) = \frac{\mathrm{Cov}[f(t), f(t+\tau)]}{V[f(t)]}, \qquad \text{if } V[f(t)] = V[f(t+\tau)] \tag{1}$$

$$= \frac{\mathrm{Cov}[f(t), f(t+\tau)]}{\sqrt{V[f(t)]V[f(t+\tau)]}} \qquad [\text{in general}]. \tag{2}$$

This kind of coefficient may be used to examine auto-correlation between two corresponding observations of the series, having the same time-lag.

If one has observations $g(t)$ for the same time periods, one can also use the cross-correlation between contemporary values of the two series $f(t)$ and $g(t)$.

$$\rho(f, g) = \frac{\mathrm{Cov}[f(t), g(t)]}{\sqrt{V[f(t)]V[g(t)]}} \tag{3}$$

Some brief remarks are needed on the effect of the irregularities of those correlation coefficients. It may be assumed that the irregularities form white noise and are uncorrelated with the systematic components (Lee *et al* 1950, Hastings and Meade 1952, Bennett 1953, Goldman 1954).

Writing

$$f(t) = r(t)+i(t) \tag{4}$$

where r and i denote respectively the systematic (or regular) and the irregular components of $f(t)$, we get

$$\begin{aligned}\mathrm{Cov}[f(t), f(t+\tau)] &= \mathrm{Cov}[r(t), r(t+\tau)]+\mathrm{Cov}[r(t), i(t+\tau)] \\ &\quad +\mathrm{Cov}[r(t+\tau), i(t)]+\mathrm{Cov}[i(t), i(t+\tau)] \\ &= \mathrm{Cov}[r(t), r(t+\tau)]\end{aligned} \tag{5}$$

in virtue of assumption stated, and

$$\begin{aligned}V[f(t)] &= V[f(t+\tau)]' = V[r(t)+i(t)] \\ &= V[r(t)]+V[i(t)].\end{aligned} \tag{6}$$

Therefore,

$$\rho(\tau) = \frac{\mathrm{Cov}[r(t), r(t+\tau)]}{V[r(t)]+V[i(t)]} \tag{7}$$

which is numerically less than the true value one would get if $i(t) = 0$ for all t

In the same way, writing

$$g(t) = r'(t)+i'(t)$$

and making similar assumptions regarding $i'(t)$, we get

$$\rho(f, g) = \frac{\mathrm{Cov}[r(t), r'(t)]}{\sqrt{\{V[r(t)]+V[i(t)]\}\{V[r'(t)]+V[i'(t)]\}}} \tag{8}$$

which again is numerically smaller than the true value of $\rho(f, g)$ that would obtain if no irregularities were present (Yule and Kendall 1940).

If, however, the irregular components of the two series $f(t)$ and $g(t)$ are inter-correlated, their presence need not lower the numerical value of $\rho(f, g)$. A similar result holds for the auto-correlation coefficient $\rho(\tau)$.

Although auto-correlation is efficacious on many occasions, cross-correlations of the time-series of observations of M and I are studied for the range of data collected in the present paper.

3. Consideration of data

The ionispheric data of Delhi, Ahmedabad, Haringhata, Kodaikanal and the meteorological data of Delhi, Ahmedabad, Alipur, Kodaikanal have been analysed and the results have been tabulated in the Table and graphically represented in Figures 1–4. The ionospheric data considered are the critical frequencies and virtual heights of (i) the normal E layer (for Delhi, Ahmedabad and Haringhata), (ii) the sporadic E layer (for Kodaikanal and Ahmedabad) and (iii) the F_2 layer (for Kodaikanal). Data of F_1 layer parameters and of $h'F_2$ parameter are not considered in the present paper. The meteorological data considered are those of barometric pressure only. With the available data, the diurnal variations of E_s layer parameters of Kodaikanal and Ahmedabad are only studied, while for seasonal variation, regular E layer parameters are studied for different stations. With the atmospheric pressure data of Colaba, a graph of 12 months' running averages of barometric pressure of Colaba vs month and year is drawn and studied (Figure 5).

A large number of data is available for the calculation of ρ for the stations mentioned in the Table and Graphs. Correlation coefficients between barometric pressure and f_0E and barometric pressure and $h'E$, for all the months of 1963 and 1968 for Delhi and the same between barometric pressure and $h'E_s$

(Day or Night), for all the months of 1963 for Kodaikanal cannot be determined for want of data

It is to be emphasized that such studies as detailed above are permissible only if the reliability of the data collected is adequate, the instruments used have identical characteristics and the standard of accuracy is also identical. These restrictions were kept in mind before considering the data for analysis.

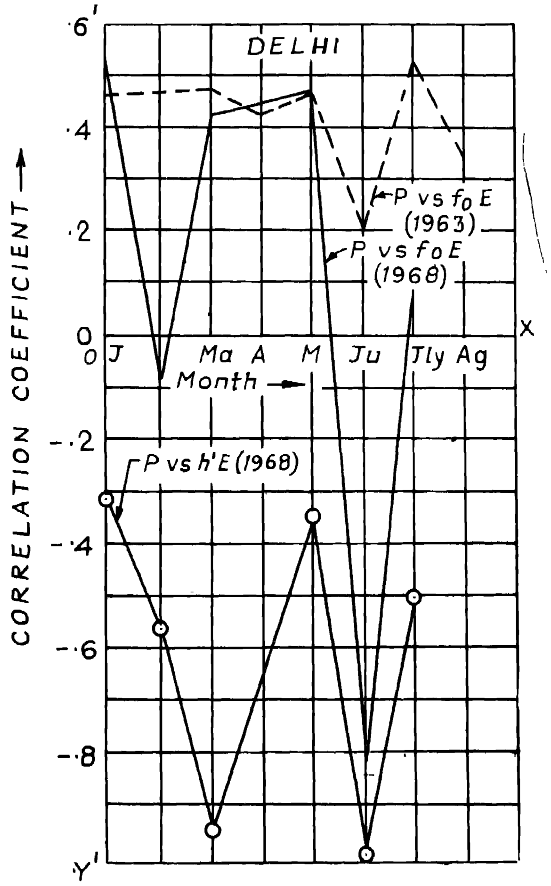

Figure 1. (Delhi) : - - - Cross-correlation between P and f_0E, 1963
— — — Cross-correlation between P and f_0E, 1968
⊙ - ⊙ - ⊙ Cross-correlation between P and h'E, 1968

4. Method of analysis

Cross-correlation coefficients of ionospheric and meteorological parameters are found by usual product-moment-correlation coefficient method (Singleton 1950, Simon 1954, Burford 1955) during different months e.g J (January), F (February), Ma (March), A (April), M (May), Ju (June), Jly (July), Ag (August) etc. and then keeping the 'Correlation Technique' (see 2) in view, these correlation coefficients are studied.

Effect of solar activity changes as a whole (i.e for all stations) as well as for individual stations, on the correlation of *I* and *M*, and the model values of this correlation from its distribution functions (Kreyszig 1969) are studied as far as possible With a chain of available stations, latitudewise study of the correlation of *I* and *M* and its model values is also made Both *D*- and *N*-time

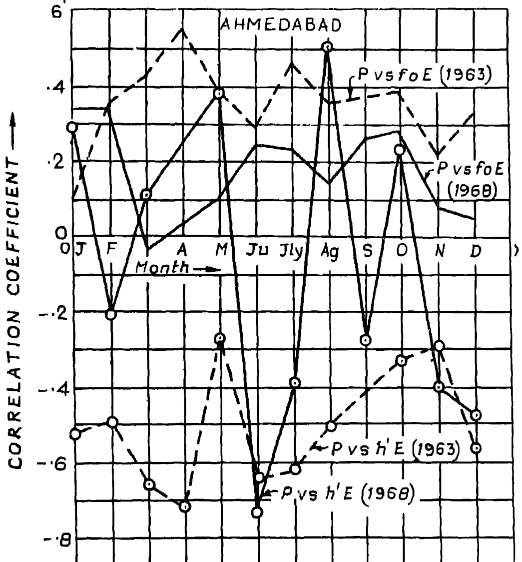

Figure 2. (Ahmedabad) Cross-correlation between P and f_0E, 1963
——— Cross-correlation between P and f_0E, 1968
⊙-⊙-⊙ Cross-correlation between P and h'E, 1963
⊙-⊙-⊙ Cross-correlation between P and *h*'E, 1968

correlations of some stations are also examined separately. Solstice effect on the correlation of M and I parameters is also studied.

All the cross-correlations are calculated by transferring the times of the data to 75°E Mean Time for all the stations excepting for Haringhata for which transfer to 90°E Mean Time is done. In all cases, with the monthly mean hourly values of the data for all 24 hours of the day, correlation coefficients are found for as many months of 1968, 1963 and 1961 as possible and for four statoions the country.

Negative correlation coefficients are taken to be the "out of phase" correlation. (Here the parameters fluctuate in the opposite sense) whereas positive correlation coefficients are the "in phase" correlation of the parameters fluctuating in the same sense. These "in phase" and "out of phase" correlations are taken to be poor, if they are below ·5, fair or moderate if near ·5 and good if above ·5. The diurnal and seasonal variations of the association of M and I fluctuations with zero hour's time lag are considered in 5 (a, b).

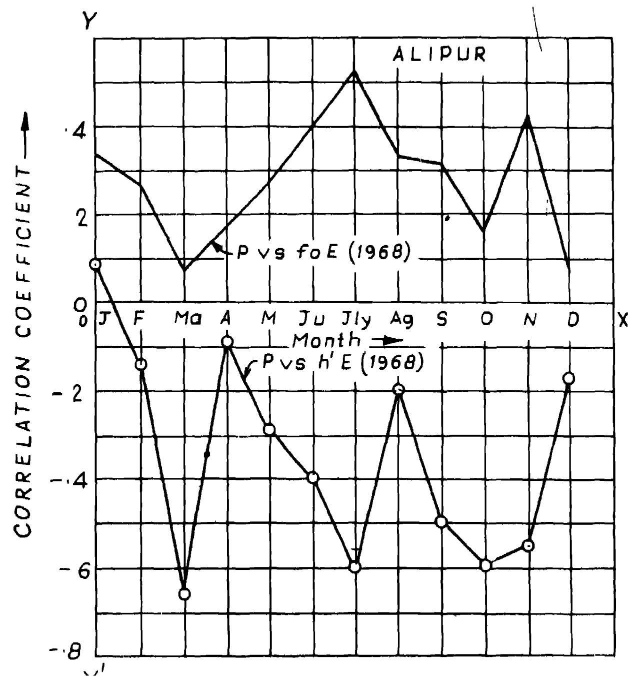

Figure 3. (Alipur) ——— Cross-correlation between P and f_0E, 1968
⊖-⊙-⊙ Cross-correlation between P and h'E, 1968

5. Results

Table 1. Correlation coefficients during different months and solstices of Delhi (28° 38′N, 77°13′E) Ahmedabad (23°01′N, 72°36′E) Alipur (22°32′N, 88°20′E), Kodaikanal (10°14′N, 77°29′E)

Correlation between (year studied)	Solstice	Station	Correlation Coefficient
P and f_0 E, 1968	Winter	Delhi	J. 5196, F-. 09164
		Ahmedabad	J.3439, F.3411, N.0860, D.0516.
		Alipur	J.3337, F.2729, N.4354, D.0747.
	Equinox	Delhi	Ma 4234
		Ahmadabad	Ma- 0384, S.2544, 0.2798
		Alipur	Ma.07866, A.1731, S 3210, 0 1595
	Summer	Delhi	M.4752, Ju-. 8235, Jly. 04559
		Ahmedabad	M.1091, Ju. 2477, Jly. 2341, Ag. 1371
		Alipur	M.2724, Ju. 4055, Jly 5335, Ag 3355
P and f_0 E, 1963	Winter	Delhi	J. 4636
		Ahmedabad	J.1166, F.3473, N.2162, D.3373
	Equinox	Delhi	Ma. 4793, A.4224.
		Ahmedabad	Ma. 4301, A.5581, 0.3928
	Summer	Delhi	M 4609, Ju 2026, Jly. 5113, A.3386
		Ahmedabad	M.3896, Ju. 2858, Jly. 4729, Ag. 3683.
P and h′E, 1968	Winter	Delhi	J-. 3138, F-.5627
		Ahmedabad	J.2929, F-.2112, N-.3969, D- 4756
		Alipur	J 0897, F-.1429, N-.5503, D-.1703
	Equinox	Delhi	Ma-.9526
		Ahmedabad	Ma 1194, S- 27880, 0.2347
		Alipur	Ma-.6628, A-.0906, S-.4979, O-.5900
		Delhi	M-. 3518, Ju-.9997, Jly.5003
		Ahmedabad	M.3848, Ju-.7442, Jly- 4013, Ag.5094
		Alipur	M-.2889, Ju-.3970, July- 6037, Ag-.1998
P and h′E, 1963	Winter	Ahmedabad	J-.5171, F-.4960, N-.2902, S-.5661
	Equinox	Ahmedabad	Ma-.6519, A-.7174, O- 3328
	Summer	Ahmedabad	M-.2667, Ju-6418, Jly- 6265, Ag-.5072;
P and f_0 E_s (D), 1963	Winter	Kodaikanal	J.8108, F.9090.
		Ahmedabad	J.1329, F 3540, N.0345, D 0206
	Equinox	Kodaikanal	Ma.8925 A 9305.
		Ahmedabad	Ma 7508, A.2852, 0.2500
	Summer	Kodaikanal	M.9234, Ju.9206, Jly. 7418, Ag. 8316
		Ahmedabad	M.5414, Ju-.4115, Jly-.0764, Ag-.7357
P and f_0E_s (N), 1963	Winter	Kodaikanal	J.1593, F.7049
		Ahmedabad	J- 7743, F-.4870, N.2341, D.2356.
	Equinox	Kodaikanal	Ma-.01106, A. 4835.
		Ahmedabad	Ma.3465, A.1303, 0.0969.
	Summer	Kodaikanal	M .4531, Ju- 1624, Jly-.4057, Ag-.5832.
		Ahmedabad	M-.4224, Ju-.6471, Jly-.4391, Ag-.6591
P and $h'E_s$ (D), 1963	Winter	Kodaikanal	J-.4111
	Equinox	Kodaikanal	Ma-.7028.
	Summer	Kodaikanal	J-.7256
P and $h'E_s$ (N), 1963	Winter	Kodaikanal	J.1649
	Equinox	Kodaikanal	Ma-.3516
	Summer	Kodaikanal	Ju.2985
P and f_0F_2, 1961	Winter	Kodaikanal	J.2898, F.4348, N.2830, D.2714.
	Equinox	Kodaikanal	Ma.5511, A.4251, S.2819, 0.2583.
	Summer	Kodaikanal	M.2810, Ju.2922, Jly. 2514, Ag. 1808.

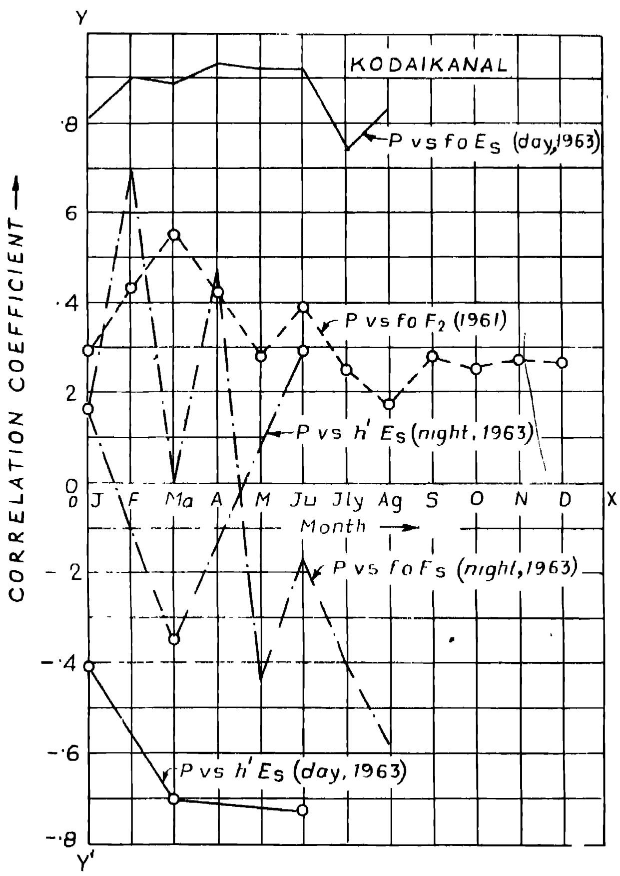

Figure 4. (Kodaikanal) Cross-correlation between P and f_0E_s, 1963 (day)
⊙–⊙–○ Cross-correlation between P and $h'E_s$, 1963 (day)
—.—.— Cross-correlation between P and f_0E_s, 1963 (night)
⊙–·–⊙–·– Cross-correlation between P and $h'E_s$, 1963 (night)
⊙– –⊙– – Cross-correlation between P and f_0F_2, 1961

(a) *Studies on Cross-correlation* (Table and Figures 1–4)
Between P and f_0E

Fluctuation is higher for Delhi than for Ahmedabad or Alipur in 1968 (Latitude effect). Nearly homogeneous and steady values for all the months of solstices of all stations in 1963 seem to have attained whereas overall fluctuation is greater for all these stations in 1968 (Sunspot Number effect) though for Ahmedabad in 1963 and 1968 nearly the same and for Delhi in 1968 higher fluctuation is observed (Again for Ahmedabad mean 'in-phase' correlation coefficient between barometric pressure and f_0E during 1963 is higher than the same during 1968).

Model value of correlation for all solar epochs and for all the available stations is seen to be within $+\cdot 32$ and $+\cdot 48$. This modal value for all the stations is again higher in 1963 than in 1968 (Sunspot Number effect).

Between P and h'E

Fluctuation in 1963 is less compared to that in 1968 for Ahmedabad (Sunspot Number effect) (Again for Ahmedabad mean 'out of phase' correlation coefficient during 1963 between barometric pressure and $h'E$ is higher than the same during 1968).

Modal value of correlation is higher at Delhi than at Ahmedabad in 1968 (Latitude effect).

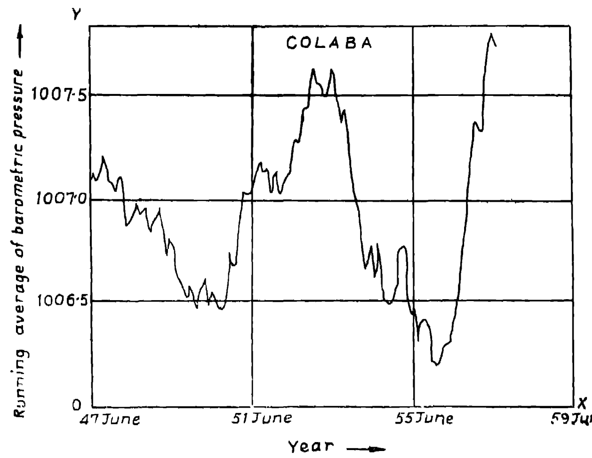

Figure 5. Graph is drawn between year and 12 months' running averages of barometric pressure of Colaba (The running average of barometric pressure for any month, say, June 1951 is taken as the mean of all the monthly average hourly values of the barometric pressure from January 1951 to December 1951).

Between P and f_0Es

Overall correlation for P vs $f_0E_s(D)$ seems to be higher for Kodaikanal than for Ahmedabad. For Ahmedabad, there are wide fluctuations, whereas for Kodaikanal this correlation is homogeneous and positive (Latitude effect). The correlation between P and f_0E_s for night and that for day for Kodaikanal or Ahmedabad are found to differ markedly during any month (Diurnal Variation). Average value of correlation between P and $f_0E_s(N)$ changes from winter to summer, for positive to negative value for Kodaikanal station (Solstice effect). This correlation between P and $f_0E_s(D)$ for the same station again increases appreciably from winter to equinox and then decreases in summer (Solstice effect). Overall impression for night-time average correlation between P and f_0E_s in 1963 is of very poor correlation for both Kodaikanal and Ahmedabad.

Model value of the day-time correlation between P and f_0E_s in 1963 lies in the range $+\cdot 80$ to $+\cdot 96$.

Between P and h'Es (Day and Night)

Correlation during night is fluctuating. Its average is very poor, whereas during day correlation is negative, high and rather stable in 1963 (Diurnal Variation).

Between P and f_0F_2

All the correlation is positive and poor or moderate. In all seasons there is a stability in the correlation. All the 12 monthly values seem to be homogeneous. (For correlation between P and f_0E_s there are both positive and negative values. Though correlation between P and f_0E seems to be broadly of the same order as that between P and f_0F_2, yet the former is appreciably higher than the latter). The modal value of correlation between P and f_0F_2 lies in $+\cdot 24$ and $+\cdot 32$.

(b) *Studies on the possible phase relation in long-term fluctuation of some M and I parameters.*

Correlation between barometric pressure and $h'E$ and that between barometric pressure and f_0E for Ahmedabad show that they are oppositely phased particularly during 1963. During 1968, this phase relationship for the same station is not clear because of greater fluctuation (Figure 2). For Delhi in 1968, this phase relation is not again clear (Figure 1). For Alipur in 1968 (Figure 3) the same phase relation between the correlation-plots of the mentioned parameters seems to exist.

(c) *Studies on long-term variation of barometric pressure with that of sunspot number (Figure 5)*

Barometric pressure fluctuation has a long term variation with the variation of sunspot numbers. The variations of barometric pressure corresponding to high and low epochs of sunspot numbers have ratio nearly 1·0014 for Colaba.

Remarks

Possible causes of variation of some correlation have been mentioned. Highest frequency functions or modal values of some correlations have been analysed for the expected causes of variation of the correlations.

It seem that the greater sunspot number in 1968 induced lesser coherent fluctuations in both pressure and critical frequency during that year and these fluctuations in these parameters were less intercorrelated. This probably explains the lesser values of cross-correlation coefficient between P and f_0E for 1968, compared to its values in 1963

The present data situation is much more complex than that usually considered in mathematical statistics for testing the homogeneity of a number of correlation coefficients. Nonhomogeneous correlations obtained in many cases may somewhat be attributed to irregularities that cannot control the required 'Standard of Coherence'.

As all calculations are based on mostly averages, about 30 (in most cases) primary observations have been averaged to get the observations actually used. This must have considerably reduced the effect of these irregularities on the results. However, it is not possible to assess their influence. Anyway, these do not change the sign of the cross-correlation coefficients which take positive or negative values, depending on whether their varitation in the two series is in phase or out of phase.

6. Test of significance

It is not possible to apply completely rigorous statistical tests of significance to assess any of the correlation coefficients. Nevertheless, one can reach at many broad conclusions, using simple non-parametric statistical tests, notably the sign test (Kendall and Stuart 1958) Thus in Figure 4, we find all the 12 monthly correlation coefficients are positive This is highly significant. In the overall, the correlation can be taken to be in phase. Similar conclusions can be reached if at least 10 correlation coefficients have the same sign

$$P\,(\text{at least 10 of the sign}) = \frac{{}^{12}C_0+{}^{12}C_1+{}^{12}C_2}{2^{12}} = \frac{79}{4096} \simeq 2\%.$$

Again in Figure 2, we find in 11 months out of 12 the positive correlation is larger during 1963 than during 1968. This difference is also significant

7. Discussion and conclusion

Correlation of fluctuation of barometric pressure and critical frequencies or virtual heights (of E_s and E layers) is often moderate and normal dependence of one parameter on other is not marked. During some months and solstices correlations (e.g. between barometric pressure and f_0E_s (Day) (or $h'E_s$ (Day)) for Kodaikanal during 1963 and between barometric pressure and $h'E$ in 1968 for Delhi) are, however, satisfactory and linear regression equations may be expected connecting the variations of the parameters. From functional distribution of the correlation coefficients, modal values of them latitudewise and with the variations of sunspot numbers (see 5a) reveal definite types of associations of the parameters

Comparative study of the trends of some correlation-plots shows that the phase changes of correlations of some I and M fluctuations seem to depend on sunspot number changes. Some correlations appear to have latitude effects on their variations (see 5a) Some biannual and annual periodicities, shown by some correlation-plots (Figures 2–4) seem to be due to the presence of these periods in the meteorological and inospheric fluctuations.

Again, E layer parameters show overall substantive (i.e. good or fair) correlation with tropospheric parameter. (E layer parameters have correlation coefficient with barometric pressure near about $\pm$·5 E_s layer ones generally more than $\pm$·5 (Table)). But F_2 layer parameter shows very poor correlation, generally below $\pm$·5

Kundu (1953) clearly explained two suggestions (Bannon *et al* 1940, Kidson 1950) for the good correlations in lower atmosphere, namely that the variations of ozone content reach the ionospheric heights and that the effects of tropospheric disturbances reach the same heights by leaking through the stratosphere. Into F_2 region, though leakage of the effects may occur, yet they cannot possibly dominate over geomagnetic, electrodynamic and other effects ruling the fluctuations there. These may be the reasons for the lesser correlation of fluctuations of F_2 region with barometric pressure

The results of analysis show that there is an appreciable coupling between tropospheric and ionospheric variations at least with variation of the lower ionosphere (E and E_s region) and the troposphere

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